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Wavefield Decomposition for Cross-line Survey

The present invention generally relates to apparatus for and methods of processing seismic data. It particularly relates to methods of performing a decomposition of a seismic wavefield into components such as up- and downgoing wavefield constituents, shear (S) and compressional (P) waves and/or other constituents of interest, where the wavefield is obtained through a cross-line survey.

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BACKGROUND OF THE INVENTION

In the field of seismic exploration, the earth interior is explored by emitting low-frequency, generally from 0Hz to 200 Hz, acoustic waves generated by seismic sources.

15 Refractions or reflections of the emitted waves by features in subsurface are recorded by seismic receivers. The receiver recordings are digitized for processing. The processing of the digitized seismic data is an evolved technology including various sub-processes such as noise removal and corrections to determine the location and geometry of the features which perturbed the emitted wave to cause reflection or refraction. The result of the processing is an acoustic map of the earth interior, which in turn can be exploited to identify for example hydrocarbon reservoirs or monitor changes in such reservoirs.

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Seismic surveys are performed on land, in transition zones and in a marine environment. In the marine environment, surveys include sources and receiver cables (streamers) towed in the body of water and ocean bottom surveys in which at least one of sources or receivers are located at the

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seafloor. Seismic sources and/or receivers can also be placed into boreholes.

The known seismic sources include impulse sources, such as explosives and airguns, and vibratory sources which emit waves with a more controllable amplitude and frequency spectrum. The existing receivers fall broadly speaking into two categories termed "geophones" and "hydrophones", respectively. Hydrophones record pressure changes, whereas geophones are responsive to particle velocity or acceleration. Geophones can recorded waves in up to three spatial directions and are accordingly referred to as 1C, 2C or 3C sensors. A 4C seismic sensor would be a combination of a 3C geophone with a hydrophone. Both types of receivers can be deployed as cables with the cable providing a structure for mounting receivers and signal transmission to a base station.

The spatial distribution of source and receiver locations in a seismic survey is referred to as layout or spread. A variety of spreads are known. Among those are spreads where receiver lines, a one-dimensional array of receiver locations, and source lines, the corresponding array of source or shot locations, are laid out at an angle. For the purpose of this invention, such layouts are referred to as "cross-line" geometry or acquisition. Such acquisitions have been described for example by G.L.O Vermeer, in "3D Symmetric Sampling", 64th Ann. Internat. Mtg: Soc. of Expl. Geophys. (1994), 906-909 and later in the United States patent no. 6,026,058.

Seismic energy acquired at a receiver may contain upwardly and/or downwardly propagating seismic energy depending on the location of the receiver and on the event. For example seismic energy when it is incident (travelling upwardly) on the water-seabed interface, be partly transmitted into the water column and partially reflected back into the seabed. Thus, a seismic event will consist purely of upwardly propagating seismic energy above the seafloor, but will contain both upwardly and downwardly propagating seismic energy below the seafloor. As another example, seismic energy when incident on the water-air interface at sea level will be reflected back into the water column generating so-called "ghost" events. It is therefore often of interest to decompose the seismic data acquired at the receiver into an up-going constituent and a down-going constituent.

Various filters that enable decomposition of seismic data into up-going and down-going constituents have been proposed. For example in "Application of Two-Step Decomposition to Multi-Component Ocean-Bottom Data: Theory and Case Study", J. Seism. Expl. Vol. 8, 261-278 (1999), K.M. Schalkwijk et al have suggested that the down-going and up-going constituents of the pressure just above the seafloor may be expressed as:

[1]

$$P^-(f, k_x, k_y) = \frac{1}{2} P(f, k_x, k_y) - \frac{\rho}{2q(f, k)} v_z(f, k_x, k_y)$$

$$P^+(f, k_x, k_y) = \frac{1}{2} P(f, k_x, k_y) + \frac{\rho}{2q(f, k_x, k_y)} v_z(f, k_x, k_y),$$

where P is the pressure acquired at the receiver, P^- is the

up-going constituent of the pressure above the seafloor, P^+ is the down-going constituent of the pressure above the seafloor, f is the frequency, k_x , k_y are the horizontal wavenumbers, v_z is the vertical particle velocity component
5 acquired at the receiver, ρ is the density of the water, and q is the vertical slowness in the water layer.

As can be seen, the expressions in equation [1] require two of the components of seismic data recorded at the receiver
10 to be combined. These expressions are examples of combining two components of the acquired seismic data. It may also be necessary to combine two or more components of the acquired seismic data in order to decompose the acquired seismic data into P-wave and S-wave components, or to remove water level
15 multiple events from the seismic data.

Further separation methods including free-surface multiple removal above the seafloor, wavefield decomposition into up- and downgoing constituents or P/S events above and below the
20 surface, the splitting of particle velocities and traction are described in a number of published documents.

In United States patent no. 6,101,408, the ocean bottom wavefield separation described in three dimensions using an
25 analytical solution. However, for practical applications, the filter is reduced to one dimension. A number of decomposition equations for various separations are developed by Amundsen et al. in the above cited United States patent no. 6,101,408 and in: "Multiple attenuation
30 and P/S splitting of multicomponent OBC data at a heterogeneous sea floor", Wave Motion 32 (2000), 67-78. A further review of decomposition methods for use in

connection with the present invention is presented by L. Amundsen in: "Elimination of free-surface related multiples without need of the source wavelet", Geophysics, Vol. 66, No. 1 (Jan-Feb 2001), 327-341.

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Approximated compact spatial filters are further described by Osen et al. in: Towards Optimal Spatial Filters for Multiple Attenuation and P/S-Splitting of OBC Data", EAGE 60th conference, Leipzig, Germany, 8-12 June 1998, 1-29
10 Geophysical Division. A short length filter is obtained in terms of powers of k_x using a series expansion.

When applying three-dimensional (3D) wavefield decomposition methods to data acquired in a cross-line geometry and sorted
15 into 1-fold bins of common mid-points (CMPs) distributed evenly in a finely spaced "carpet" determined by in-line source and receiver spacings as proposed by Vermeer, it was noted that the known filter introduce an unacceptable level of noise due to sensor variations, statics and other
20 perturbations.

In the light of the above prior art, it is seen as an object of the present invention to provide filters applicable to cross-line acquisitions or data collected through cross-line
25 acquisitions and methods of applying such filters.

SUMMARY OF THE INVENTION

According to a first aspect of the invention there is
30 provided a method of decomposing a seismic wavefield, wherein a 3D wavefield is obtained by a cross-line acquisition and filtered applying a decomposition filter

having two spatial components or filtering in two spatial directions to obtain a decomposed representation of the wavefield.

- 5 A 3D wavefield for the purpose of this invention involve obtaining data or time series of measured parameters over an area. Hence, such data are acquired as series of ideally closely spaced parallel lines. The parameters measured are preferable velocity and pressure data.

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In the cross-line acquisition shot lines and receiver lines enclose an angle, which is preferably around 90 degrees.

- 15 The method of this invention can be applied to any of the existing decomposition equations that include a filter term depending on the vertical wavenumber k_z . Such decompositions preferable include up- / down going decomposition, P/S decomposition, elastic decomposition and acoustic decomposition.

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- The filter of the present invention has two spatial components that when represented in an analytical form are written as k_x and k_y , or as spatial derivatives in x and y , respectively. When implemented as machine program these
25 filters are approximated by finite differences.

The filter is preferably a cascaded filter of 1D spatial filters that are applied sequentially.

- 30 The filter is preferably a compact filter having a finite length or support in in-line and cross-line direction. When analytically derived, wavefield decomposition filters have

infinite extent or support in space and in time. The filter operations generally assume stationary medium properties or in the case of deghosting a locally flat sea surface (both in time and space). The main advantage of introducing compactness is to ensure that medium properties (or sea surface variations) are constant across the aperture (or two dimensional support) of the filter. For the seabed wavefield decomposition filters the full analytical expression of the filter can be written in the frequency wavenumber domain for instance. The infinite support in time can be maintained since medium properties do not vary with time. However, in the spatial directions Taylor expansions of the filter into factors k_x , k_x^2 , k_x^3 , ..., k_y , k_y^2 , k_y^3 , ... are proposed. When going back to the spatial domain each factor k_x or k_y or its powers simply correspond to a derivative in the x- and y-directions respectively. Spatial derivatives can in turn be implemented with compact local support using 2-point, 3-point, 5-point, or more extended FD approximations. However, there are also other ways of designing compact filters without necessarily relating them to spatial derivatives.

Preferably the spatial filter of the present invention is applied exclusively to the measured pressure wavefield $P(f, k_x, k_y)$. The pressure measurement is usually less sensitive to mismatch in the response of the various receivers used to record the wavefield.

It is furthermore advantageous to use a calibration for matching geophone recordings with hydrophone recordings prior to the decomposition filtering, particularly in case

the filter operates on the particle velocity (v_x, v_y, v_z)

After the decomposition filter is applied it is possible to remove multiples or proceed with other known steps to obtain
5 an image of sub-surface, including migration and other methods known in the art.

These and other aspects of the invention will be apparent from the following detailed description of non-limitative
10 examples and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A illustrates an ocean bottom acquisition of a 3D seismic wavefield using an OBC and a source towed
15 by a seismic vessel;

FIG. 1B illustrates the spread of data point after shooting a single shot line of the acquisition of FIG. 1A;

20 FIG. 1C illustrates the acquisition of 3D seismic wavefield using streamers towed by a first vessel and a source towed by a second seismic vessel;

FIG. 2 is a diagram illustrating steps in accordance with
25 an example of the invention; and

FIG. 3 compares the performance of filter approximations s in accordance with examples of the invention.

30 EXAMPLES

In FIG.1A there is illustrated an example of a seismic survey in cross-line geometry. The survey is a marine

seismic survey in a body of water 10 between a seafloor 101 and a sea surface 102. A receiver cable 11 with a plurality of receivers 111 is laid out on the seafloor 101. The receivers 111 are preferably 4C sensors, though, as will be apparent from the following description, the sensors may comprise a 1C geophone and a hydrophone only, being thus capable of recording at least the vertical component of velocity and pressure at seafloor level.

10 A seismic vessel 12 tows a marine seismic source 13 close to the sea surface 102. The airgun 13 emits at precisely determined time intervals an impulse of acoustic energy referred to as "shot". A dashed line 132 indicates the path of the towed airgun 13. The projection 133 of the dashed line 132 onto the seafloor 102 intersects the receiver line 112 at approximately 90 degrees. Though it is preferable to aim for a near-orthogonal orientation of receiver lines to shot lines, deviations are inevitable under real survey conditions. To facilitate the following description the receiver line or in-line direction is denoted as x direction, the shot-line or cross-line direction is marked as y direction and the vertical direction is taken as the z direction.

25 During a survey, the sources 131 are fired at intervals and the receivers 121 "listen" within a frequency and time window for acoustic signals such as reflected and/or refracted signals that are caused features in path of the emitted wavefield. After shooting a line, the vessel performs a u-turn in order to shoot a subsequent line usually with an offset in receiver line or x direction.

In the general practice, it is assumed that Green's functions which describe the wave propagation between source and receiver points are invariant for translation of the source and receiver in the cross-line direction. Hence, an
5 offset between shooting lines can be regarded as an equal shift of the receiver line. As a result, data points obtained from a single source cross-line form a carpet on the seafloor, which is illustrated in FIG. 1B. In FIG. 1B, the triangles 122 denote the location of data points. As
10 the wavefield is recorded in two spatial dimensions and in time, the resulting data are referred to as 3D wavefield.

In FIG. 1C, there is shown a schematic cross-line marine survey with two vessels. A first vessel 15 tows five
15 streamers 151 below the sea surface following a path 152. Simultaneously, a second vessel 16 on path 162 tows a seismic source 161 below the surface. As above in Fig. 1A, the resulting shot and receiver lines are essentially orthogonal to each other.

20 In the following description and the accompanying FIG. 2, steps are described leading to a decomposition of the 3D wavefield into up- and downgoing components.

25 After obtaining 20 the wavefield data set as acquired through the seismic receivers, the data are first preferably calibrated 21 to compensate for the differences between geophone and hydrophone recordings. Any suitable calibration may be used including for example the methods
30 described in the International patent application PCT/GB03/04190. Following those methods, the calibration can be done using an in-line shot-line for the P , v_z and v_z

components and using a cross-line shot-line for the v_y component.

Acoustic wavefield decomposition 22 is usually carried out on the pressure component P (involving spatial filtering of v_z). Instead in this example decomposition filters are applied to the vertical geophone component v_z (involving spatial filtering of P). The advantage of this example is that the spatial components of the filter only act on P as shown in PCT/GB03/04190.

Accordingly, acoustic wavefield decomposition into up- and down-going constituents above the seafloor can be achieved by solving the following equation:

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[2]

$$v_z^{\pm}(f, k_x, k_y) = \frac{1}{2} a(f) v_z(f, k_x, k_y) \pm \frac{k_z(f, k_x, k_y)}{2\rho\omega} P(f, k_x, k_y)$$

In equation [2], $a(f)$ denotes the optional frequency-dependent calibration filter that corrects for imperfections in the recording of the geophones, v_z^- denotes the up-going constituent of the vertical component of particle velocity, and v_z^+ denotes the down-going constituent of the vertical component of particle velocity. The velocity v_z is the recorded or estimated vertical component of particle velocity in the frequency f - wavenumber domain, $P(f, k_x, k_y)$ is the recorded pressure, and ρ is the density in the recording medium.

30 The term k_z , which can be expressed as

$$[3] \quad k_z(f, k_x, k_y) = \sqrt{(2\pi f/c)^2 - k_x^2 - k_y^2} \quad ,$$

is the absolute value of the vertical wavenumber expressed in terms of horizontal wavenumbers in the in-line direction k_x and the cross-line direction k_y , and the velocity c of the recording medium. It should be noted that the decomposition could also be achieved by computing the up-going component of the recorded pressure P^- using equations [1], leading expression which include terms of $1/k_z$. Such terms can be approximated using similar expansions as described below.

In known decomposition methods using any of the above equations [1,2], the cross-line or y-directions is mostly ignored or a radial symmetry is assumed, with the vertical wavenumber then being computed using an approximation based exclusively on a one-dimensional direction, i.e. the in-line wavenumber k_x or the radial wavenumber k_r . When 3D effects of the sub-surface or acquisition geometry are significant, such approximations are no longer valid.

Equations as those described herein can be implemented in the common mid-point domain, which is proposed by Vermeer (1994) and Thomas (2000). It is however fruitful to rewrite or approximate equation [3] into a form constituting a cascade (sum or product) of one-dimensional (1D) spatial filters acting in the x- or y-directions only. This represents a computationally attractive way of filtering the data (both in terms of CPU and resorting data between different domains). One way to obtain filters of this form is to make suitable Taylor expansions of the horizontal wavenumbers in the square-root term around zero wavenumbers.

This approximation remains valid for data corresponding to propagating waves at $k_x^2 + k_y^2 < (2\pi f/c)^2$.

5 The expression for the vertical wavenumber can be rewritten and expanded in k_x and k_y to produce a few different alternative expansions that can be implemented using a cascade of filters that only act in the cross-line or in-line direction one at a time:

10 [4a]

$$k_z(f, k_x, k_y) \approx$$

$$\sqrt{(2\pi f/c)^2 - k_x^2} \left(1 - \frac{k_y^2}{2((2\pi f/c)^2 - k_x^2)} - \frac{k_y^4}{8((2\pi f/c)^2 - k_x^2)^2} + O(k_x^6, k_y^6) \right).$$

[4b]

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$$k_z(f, k_x, k_y) \approx$$

$$2\pi f/c \left(1 - \frac{k_x^2 + k_y^2}{2(2\pi f/c)^2} - \frac{k_x^4 + k_y^4 + 2k_x^2 k_y^2}{8(2\pi f/c)^4} + O(k_x^6, k_y^6) \right).$$

[4c]

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$$k_z(f, k_x, k_y) \approx$$

$$\sqrt{(2\pi f/c)^2 - k_x^2} + \sqrt{(2\pi f/c)^2 - k_y^2} - 2\pi f/c \left(1 + \frac{2k_x^2 k_y^2}{8(2\pi f/c)^4} + O(k_x^6, k_y^6) \right)$$

Equations [4a-4c] represent different ways to proceed with an implementation of the filter with two spatial components that only rely on being able to filter the data along two perpendicular spatial directions one at a time which is exactly what can be achieved using the method described above in a cross-line geometry. Note that this does not mean that only a "cross" of mid-points are used in filtering the data. All cross-terms of multiplications of terms with different horizontal wavenumbers will result in a "virtual" carpet of data being used of dimension of the length of the spatial filters in both directions.

After the decomposition 22, multiples could be removed 23 from the data set. Further processing steps and/or filtering steps 24 could be performed on the decomposed data set. Using what is commonly referred to as imaging or migration 25 the data set can be further processed to yield an image of subterranean layers. These images are used for hydrocarbon exploration and reservoir characterization. The optional steps 21 and 23 - 25 are indicated in FIG. 2 as dashed blocks.

FIG. 3 shows a panel of the exact wavefield decomposition filter using equation [3] in the top left, difference between equation [3] and the filter approximation [4a] in the top right, difference between equation [3] and the

filter approximation [4b] in the bottom left, and difference
between equation [3] and the filter approximation [4c] in
the bottom right. Note that these plots only assess the
accuracy of the filter approximations and do not include the
5 error due to their discretization. In other words, the
plots do not show inaccuracies related to how the different
terms in the spatial filter approximations [4a-4c] are
implemented (e.g., using 3-point or 5-point derivative
approximation). This would of course introduce a dependence
10 on frequency as well. However, this is of secondary
importance as appropriate approximations that are
sufficiently accurate are straightforward to find.

From the top right of FIG. 3, it can be seen that equation
15 [4a] which was obtained by making a Taylor expansion in the
y-direction only results in the best approximation of the
three examples for azimuths close to the in-line cable
direction. Equation [4b] which is used in the difference
plot at the bottom left of FIG. 3 results in an
20 approximation which is equally good along all azimuths. An
advantage with this filter is that it can be fully
implemented as a compact filter. Equation [4c] which is
used in the difference plot at the bottom right of FIG. 3
results in a fully accurate approximation both along the in-
25 line and cross-line azimuths. The filter can be implemented
using a compact filter approximation for the cross-term
only. Exactly which of the alternative implementation [4a-
4c] that is most attractive may vary depending on different
combinations of requirements in terms of computational cost
30 (CPU and data access) and accuracy.

- While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, 5 the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.
- 10 The above approximations or similar approximations can be used for example with the separations developed by Amundsen et al. in the above cited United States patent no. 6,101,408 or in: "Multiple attenuation and P/S splitting of multicomponent OBC data at a heterogeneous sea floor", Wave 15 Motion 32 (2000), 67-78. In the latter document, demultiple or decomposition equations are found for elastic decomposition (particle velocity, traction) or P/S wave splitting below the sea floor.